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EXPERIMENTAL PROBES OF HIGGS BOSONS AND ELECTROWEAK SYMMETRY BREAKING*

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ABSTRACT

Our present understanding of the best means for detecting Higgs bosons and exploring direct manifestations of electroweak symmetry breaking is outlined. In particular, we review the recent developments that have led to the conclusion that the Standard Model Higgs boson can be found and/or the WW scattering sector explored at the SSC for any Higgs mass between the upper reach of LEP-II and about 1 TeV. In the case of the Minimal Supersymmetric Model, the regions of model parameter space in which viable Higgs boson signals emerge at the SSC and LHC are delineated for the cleanest discovery modes. We explain why one is close to having a no-lose theorem: namely, throughout nearly all of parameter space one or more of the MSSM Higgs bosons can be discovered either at LEP-II or using relatively background-free modes at the SSC or LHC, independent of the value of m_t. A brief outline of how to detect the Minimal Supersymmetric Model Higgs bosons at a $\sqrt{s} \gtrsim 300$ GeV linear e^+e^- collider is also given.

1. Introduction

The last year has brought substantial progress in demonstrating that the Higgs boson/Electroweak Symmetry Breaking sectors of two of the most attractive theoretical models (the Minimal Standard Model, SM, and the Minimal Supersymmetric Model, MSSM) can be explored either at LEP-II or at the SSC/LHC for all reasonable parameter choices (*e.g.* the top quark mass, the Higgs mass(es), *etc.*). These are important benchmarks in establishing our ability to either discover or exclude elementary scalar bosons for all masses and models. I shall review the crucial ingredients in this progress and the current status of the situation. Overall, it is important to keep in mind that even if a SM-like Higgs boson is found at LEP/LEP-II, it will still be necessary to: a) look for other scalars of possible extended Higgs sectors; b) check that $V_L V_L$ ($V = W, Z$ and L stands for longitudinal polarization) scattering follows the perturbative SM prediction; and c) study the properties of

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all scalars that are detected. These items will be the exclusive province of the SCC/LHC hadron colliders and the next high energy (linear) e^+e^- collider (NLC). This review will therefore focus upon these colliders.

2. The Standard Model

Should the Standard Model Higgs boson, ϕ^0, have mass $\lesssim m_Z$, then it will be discovered at LEP-II. For masses above this, future hadron supercolliders such as the SSC and LHC have been shown to provide a fairly ideal laboratory for the search for the Standard Model Higgs boson. (For reviews and references to older results see Ref. [1]; newer developments are surveyed in the reports of Refs. [2,3,4].) The mass region $2m_Z \lesssim m_{\phi^0} \lesssim 700 - 800$ GeV is easily probed via the 'gold-plated' mode $\phi^0 \to ZZ \to l^+l^-l^+l^-$ ($4l$, for short). The $\phi^0 \to ZZ^* \to 4l$ mode, first considered in Ref. [5], allows ϕ^0 detection for ~ 135 GeV $\lesssim m_{\phi^0} \lesssim 2m_Z$. However, until recently, a clear Higgs boson signal had proved elusive for Higgs masses below ~ 135 GeV. And for very large m_{ϕ^0}, a clearly viable technique for exposing the predicted strong interactions in the WW scattering sector at energies $\gtrsim 1$ TeV had not been developed.

1.1. The Low Intermediate Mass Range: $80 \lesssim m_{\phi^0} \lesssim 135$ GeV

An example of the problems encountered in this mass region are those found in attempting to detect the ϕ^0 in inclusive production, followed by $\phi^0 \to \gamma\gamma$. A viable signal in this channel emerges only if very excellent $\gamma\gamma$ mass resolution and $\gamma - jet$ rejection is possible.[5] (For a recent experimentally oriented summary see Ref. [2].) A typical SSC detector, such as that proposed by the SDC collaboration,[6] will not have the required resolution and jet rejection. The recent developments that have filled the 80 GeV $\lesssim m_{\phi^0} \lesssim 135$ GeV gap between the lower limit of the $ZZ^* \to 4l$ channel and the approximate upper limit for ϕ^0 discovery at LEP-II focus on $W\phi^0$ associated production.

First, $W^* \to W\phi^0$ production followed by $W \to l\nu$ and $\phi^0 \to \gamma\gamma$ was proposed as a relatively background free channel.[7,8,2] Indeed, one finds that the backgrounds, primarily from $W\gamma\gamma$ and $W\gamma\, j$ continuum production,[7,8] are substantially smaller than the signal.† However, the event rate for $W^* \to W\phi^0 \to l\gamma\gamma X$ is so low that an integrated luminosity of $L = 100$ fb^{-1} (*i.e.* ten times the canonical SSC yearly luminosity) would have been required to achieve a significant signal for a ϕ^0 with mass between ~ 80 GeV and ~ 150 GeV.

A dramatic improvement of the situation has been the observation[9,10] that this same $W\phi^0 \to l\gamma\gamma X$ final state emerges from $t\bar{t}\phi^0$ production (which has a very

† Of course, appropriate cuts on both signal and background are required; for details see the quoted references.

substantial rate for moderate m_{ϕ^0}) in which one of the t's decays to the leptonically decaying W. The $l\gamma\gamma X$ rate due to the $t\bar{t}\phi^0$ process is about 4 to 5 times greater than that for the W^* process at the SSC. Further, the $t\bar{t}\gamma\gamma$ background has been shown to be small unless $m_t \lesssim 120$ GeV.[11,12] Still awaiting a fully quantitative study are the $t\bar{t}jj$ and $t\bar{t}\gamma j$ event rates. A major component of the former was evaluated in Ref. [13], and found to be completely negligible for easily achieved jet-γ discrimination factors. The latter is currently being evaluated.[14] A crude estimate performed in Ref. [13] suggests that it should be manageable.

Including the $W\gamma\gamma$, $t\bar{t}\gamma\gamma$, and $W\gamma j$ backgrounds (with a $\gamma - j$ rejection factor of $R_{\gamma j} = 5 \times 10^{-4}$), one obtains a viable ϕ^0 signal at the SSC throughout the 80 GeV $\lesssim m_{\phi^0} \lesssim$ 135 GeV mass region for the canonical $L = 10$ fb^{-1} of integrated luminosity. (At the LHC, L substantially above 10 fb^{-1} continues to be required, but the full 100 fb^{-1} enhanced luminosity is not necessary.) Illustrative SSC results at $L = 10$ fb^{-1} are those for $m_{\phi^0} = 110$ GeV. For SDC detector resolutions[6] a bin size of about 4 GeV in $M_{\gamma\gamma}$ is appropriate, and for $m_t = 150$ GeV one obtains (for SDC detector acceptances and after appropriate cuts) $S/\sqrt{B} \simeq 25/\sqrt{8} \sim 9$, where ~ 21 of the signal events are from $t\bar{t}\phi^0$ and ~ 3 of the background events are from $t\bar{t}\gamma\gamma$. For $m_t = 100$ GeV, the $t\bar{t}\gamma\gamma$ background increases significantly, leading to $S/\sqrt{B} \simeq 25/\sqrt{16} \sim 6$, still a viable signal. For m_{ϕ^0} values either above or below 110 GeV the $S/\sqrt{B}$ values deteriorate somewhat, but so long as $m_t \gtrsim 120$ GeV, $S/\sqrt{B} \gtrsim 4$ is achieved throughout the 80 $\lesssim m_{\phi^0} \lesssim$ 140 GeV mass range. Also noteworthy is the fact that for $L = 100$ fb^{-1} at the SSC, the event numbers are sufficient that the W^* and $t\bar{t}\phi^0$ processes can be separated from one another (by jet-antitagging or tagging), thereby allowing separate determination of the $WW\phi^0$ and $t\bar{t}\phi^0$ couplings, respectively. (However, this might not be possible at the LHC.) In any case, we can now say with confidence that the full Intermediate Mass range of the SM Higgs can be explored at the SSC.

1.2. A Strongly Interacting WW Sector

Should there be no light ($\lesssim 1$ TeV) Higgs boson, then either $V_L V_L$ scattering becomes strong at subprocess energies of order 1 TeV or some other new physics will be produced in $V_L V_L$ initiated processes. The former scenario has received much attention on the theoretical front (see the many contributions to the proceedings of this conference), but there are many potential difficulties associated with obtaining a viable experimental signature for strong $V_L V_L$ scattering. The magnitude of the problem depends critically upon the exact strength of the strong interactions in the LL sector. Certainly there are models which predict dramatic resonance effects that would be hard to miss. On the other hand the SM with $m_{\phi^0} \sim 1$ TeV exhibits only rather mild enhancements of $V_L V_L$ scattering at TeV subprocess energy scales.‡ Until

‡ While the SM with $m_{\phi^0} \gtrsim 1$ TeV is not a fully consistent theory unless supplemented by

this last year, techniques for isolating such mild effects had not been definitively established.

There are two basic problems. The very clean 'gold-plated' mode, $ZZ \to 4l$, has too low an event rate in the SM for $m_{\phi^0} \sim 1$ TeV for a viable signal at $L \sim 10$ fb^{-1} at the SSC. Secondly, backgrounds to the mixed hadronic/leptonic modes such as $W^+W^- \to l\nu q\bar{q}$, which have much larger event rates, are very substantial. Despite the many promising suggestions as to how to isolate a signal in such a channel (see Ref. [1] for a review), all techniques suffer from theoretical and/or experimental uncertainties. For these reasons, the viability of using the purely leptonic final states of $W^\pm Z$, $W^\pm W^\mp$ and $W^\pm W^\pm$ production, in order to isolate a signal for enhanced $V_L V_L$ scattering when $m_{\phi^0} \sim 1$ TeV, has been recently explored by several groups. Since the $V_L V_L$ enhancement is very broad ($\Gamma_{\phi^0} \geq 500$ GeV) for such large m_{ϕ^0}, the inability to explicitly reconstruct the VV mass (due to missing neutrinos) in these alternative channels is not as much of a loss as it seems at first sight. The main question is whether one can isolate the $V_L V_L$ scattering signal from backgrounds.

Here we shall focus on the $W^+W^+ \to l^+l^+ + X$ channel.[§] The importance of the like-sign dilepton spectrum as a means of detecting strong scattering of longitudinally polarized W^+'s has been frequently discussed.[15-17] In particular, this channel has an advantage over the $W^\pm Z$ and $W^\pm W^\mp$ channels in that there is no W^+W^+ continuum pair production arising from $q\bar{q}$ annihilation. The only irreducible background to $qq \to qqW_L^+W_L^+$ production is that from $qq \to qqW_T^+W_T^+ + qqW_T^+W_L^+$ production — *i.e.* all possible polarization combinations are inevitably produced in the sum over $qq \to qqW^+W^+$ subprocess diagrams. The crucial reducible background is that from $t\bar{t}$ production followed by $t \to bW^+ \to bl^+\nu$ and $\bar{t} \to \bar{b}W^- \to \bar{c}l^+\nu jj$, in which one of the like-sign dileptons arises from semi-leptonic $\bar{b}$ decay. The event rate for this $t\bar{t}$-induced reducible background is very large. Efficient techniques for suppressing the irreducible background from real $W_T^+W_T^+ + W_T^+W_L^+$ production were established in Refs. [18] and [19]; complementary work has appeared in Ref. [20]. In particular, in Refs. [18] and [19] it was found that anti-tagging against energetic jets produced in association with the like-sign leptons, in addition to strong p_T and back-to-back cuts on the leptons, was very effective in discriminating against events containing one or more transversely polarized W^+'s in the final state, while at the same time allowing retention of most events in which both W^+'s are produced with longitudinal polarization. Techniques for successfully suppressing the $t\bar{t}$-induced background were developed in Refs. [19,21]. Below, we sketchily review the procedures and summarize the final event rates.

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additional new physics at the TeV scale, the small size of perturbatively computed higher order corrections for VV masses in the 1 to 2 TeV range suggests that a fully consistent theory could be constructed with rather similar VV phenomenology.

§ For notational simplicity we do not *explicitly* discuss the corresponding W^-W^- channel.

First, it is necessary to define precisely what the signal for $V_L V_L$ production is. In the absence of any cuts on outgoing particles, it has long been known (see, *e.g.*, Refs. [15] and [20]) that the entire difference between VV production at large m_{ϕ^0} and at small m_{ϕ^0} is due to LL final states; at small m_{ϕ^0}, TT and TL modes are the only ones of importance, and their contribution remains unchanged as m_{ϕ^0} increases. In Refs. [18], [19], and [21] it was shown that even after severe cuts on the leptons this still remains true. Thus, for $m_{\phi^0} = 1$ TeV, the signal of interest is defined as

$$S \equiv \int \frac{d\sigma}{dM_{ll}} dM_{ll}\Big|_{m_{\phi^0}=1 \text{ TeV}} - \int \frac{d\sigma}{dM_{ll}} dM_{ll}\Big|_{m_{\phi^0}=50 \text{ GeV}} , \tag{1}$$

where M_{ll} is the l^+l^+ pair invariant mass, and we have taken $m_{\phi^0} = 50$ GeV as the low Higgs mass comparison point (sensitivity to this exact choice is very small). The irreducible background B is defined as the magnitude of the second term in Eq. (1). In Table 1 we display the event rates for S, B and $B_{t\bar{t}}$ (the latter being the reducible $t\bar{t}$-induced background computed in the worst case — $m_t = 200$ GeV) after various cuts. In the first row of Table 1, we require $M_{ll} > 300$ GeV, and $p_T^l > 75$ GeV and $|y_l| < 3.5$ for both l^+'s (requiring $|y_l| < 2.5$ reduces the rates only slightly). Note that B would hide S even without the enormous $B_{t\bar{t}}$ background. Next, in the second row of the Table, we force the leptons to be very back-to-back by demanding that $\cos\phi_{l_1^+ l_2^+} \leq -0.8$ and $|\vec{p}_T^{\,l_1^+} - \vec{p}_T^{\,l_2^+}| \geq 200$ GeV. Both B and $B_{t\bar{t}}$ are reduced somewhat. Next, we anti-tag by discarding events with central ($|y| < 5$) energetic jets having $p_T^{jet} > 125$ GeV. At this point $B < S$, but $B_{t\bar{t}}$ is still very big. That B should be suppressed, in comparison to S, after back-to-back cuts and anti-tagging follows from a basic physical difference between LL production and $TT+LT$ production. In LL production, *both* final V_L's are produced from the scattering of two initial V_L's which, in turn, arise from $q \to V_L q$ virtual bremsstrahlung. These initial V_L's are produced with a dp_T^2/p_T^4 spectrum, *i.e.* very sharply peaked at small p_T, in comparison to initial V_T's that are produced with a dp_T^2/p_T^2 spectrum in $q \to V_T q$ bremsstrahlung. As a result, in $V_L V_L \to V_L V_L$ scattering the final V_L's are very back-to-back (and, hence, so are highly energetic leptons from their decays) and, as well, the spectator final state q jets *both* have very small p_T, in comparison to processes yielding one or more final V_T's.

But, to conquer the $t\bar{t}$ background, $B_{t\bar{t}}$, requires one or more dramatically effective new cuts. Two possibilities were identified in Refs. [19] and [21]. The first involves the explicit tagging of one (or more) jets (as found after allowing for jet-coalescence in the detector).[22] For any tagged jet, we require $p_T^j > 30$ GeV, $|y_j| < 5$, and $\Delta R_{jl} > 0.5$. Since our main goal at this point is to suppress the $t\bar{t}$-induced background, in which (before jet-coalescence) there are generally at least 4 energetic jets — the b, $\bar{b}$, and the two jets from the W^- decay, we also require that there be no more than 2 such tagged jets. The signal generally has only the

Table 1: Event rates at the SSC (for $L = 10$ fb^{-1}) for the LL signal, S, irreducible background, B, and $t\bar{t}$-induced background (for $m_t = 200$ GeV), $B_{t\bar{t}}$, after different types of cuts (see text). In the first row, only lepton y and p_T cuts are imposed. In the second row, back-to-back cuts on the leptons are imposed *in addition*. In the third row, the anti-tagging cut is added to the previous two cuts. Parenthetical numbers indicate event rates obtained at each cut level if, as well as the indicated cut, one or more spectator jets is tagged (subject to the requirements discussed in the text). In the fourth row, jet-tagging is required and the $M_{jl}^{\min}$ cut is imposed in addition to all the previous cuts. In the fifth row, the isolation cut is imposed on top of the the cuts of the first three rows (lepton, back-to-back, and anti-tagging), but no explicit jet tagging is required.

Cut	S	B	$B_{t\bar{t}}$
basic lepton requirements	12	60	10^4
$\lvert y_l\rvert < 3.5$, $p_T^l > 75$ GeV, $M_{ll} > 300$ GeV	(12)	(53)	(660)
back-to-back lepton cut	11	27	8900
$\cos\phi_{l_1^+ l_2^+} \leq -0.8$, $\lvert\vec{p}_T^{\,l_1^+} - \vec{p}_T^{\,l_2^+}\rvert \geq 200$ GeV	(22)	(23)	(470)
anti-tagging	8	4	3300
$p_T^j < 125$ GeV if $\lvert y_j\rvert < 5$	(8)	(4)	(330)
$M_{jl}^{\min} > 200$ GeV	(6.5)	(2)	(1)
isolation	8	4	< 1

two energetic spectator jets appearing in the $qq \to qqW^+W^+$ subprocess, and is not significantly reduced by such a cut so long as the p_T^j threshold chosen above is sufficiently large that extra jets from initial and final state radiation are likely to have p_T's below this threshold. The event numbers obtained after such tagging requirements are imposed, in addition to each of the previously discussed cuts, appear in parentheses in the first three rows of Table 1. Clearly, the $t\bar{t}$ background, $B_{t\bar{t}}$, has been greatly suppressed, but not yet to a level below S. To kill $B_{t\bar{t}}$, we compute the minimum invariant mass, $M_{jl}^{\min}$, between the tagged jet(s) and either of the two leptons. For the signal, any tagged jet will be one of the energetic spectator jets in the $qq \to qqW^+W^+$ subprocess. The invariant mass of such a forward energetic jet in combination with one of the energetic l^+'s at small rapidity will tend to be quite large. In contrast, lowest order parton level $t\bar{t}$ production and decay only yields events with $M_{jl}^{\min} < m_t$. After including jet smearing and extra (final or initial state) gluon radiation, a small tail in the $M_{jl}^{\min} > m_t$ region emerges, but Table 1 shows that this tail yields a contribution to $B_{t\bar{t}}$ that is substantially below the signal, S.

The second possibility for eliminating $B_{t\bar{t}}$ is to require that *both* leptons be isolated from associated hadronic energy in the same direction. (Obviously, the l^+ emerging from $\bar{b} \to \bar{c}l^+\nu$ decay in the case of the $t\bar{t}$ background will not be isolated from the $\bar{c}$.) The explicit means of implementing such a cut, and its ultimate effectiveness, are highly detector dependent. One possibly big problem, for instance, is how to fully separate the hadronic energy of the $\bar{c}$ jet from the leptonic energy of the associated l^+. Since both will enter the same detector cell, this separation cannot be achieved with arbitrarily great precision. In Table 1 (the fifth row) we give the event rates that would result if the only limitation on isolation were to be the detector smearing of the *individual* lepton and jet energies. (For specific details concerning the smearing and exact isolation cut, see Ref. [21].) In this ideal case, we see that the $t\bar{t}$ background can be eliminated even in the absence of jet-tagging. In practice, some combination of isolation and jet-tagging may be necessary. For instance, one could tag one or more jets and then impose isolation without imposing the $M_{jl}^{\min}$ cut. For this scenario, the parenthetical event rates of Table 1 show that to eliminate $B_{t\bar{t}}$ in each of the first three rows one would need a suppression factor from isolation of order only ~ 100 instead of the ~ 1000 required in the absence of any jet-tagging.

Given that we are confident that one of the two procedures, or some combination thereof, can be implemented, the bottom line is apparent. For $L = 10$ fb^{-1} we can obtain of order $S = 8$ signal events (note that our procedures were about 65% efficient for the signal), with small background. Adding in the W^-W^- channel yields about 12 signal events. This may still be slightly too few events to claim an incontrovertible signal for the modest amount of strong $W_L^\pm W_L^\pm$ scattering predicted for $m_{\phi^0} \gtrsim 1$ TeV in the Standard Model, but $L = 20 - 30$ fb^{-1} would certainly yield enough events. Of course, for many other (*e.g.* technicolor) models, the $W_L^\pm W_L^\pm$ signal is likely to be even larger and correspondingly less luminosity would be required for its detection.

Three final points are of importance. First, suppose that one of the SSC detectors is such that lepton isolation (either with or without jet-tagging) can be used to eliminate $B_{t\bar{t}}$ at each of the first three cut levels of Table 1. Then, if there is no $W_L^\pm W_L^\pm$ production (as is the case if m_{ϕ^0} is small), the event rates after each of the three successive cuts should follow the pattern predicted by B. Observation of this pattern, with no S component emerging after the third (anti-tagging) cut, would provide a direct measurement of the $TT + LT$ production cross section and a confirmation that $W^\pm W^\pm$ production is following the small-m_{ϕ^0} perturbative prediction. Second, we note that the full procedure based on the $M_{jl}^{\min}$ cut can be expected to work equally well for isolating the LL signal in all the other purely-leptonic final state channels of VV production.* This is because jet-tagging, as implemented in

* An isolation cut is no longer particularly useful. In particular, in the $t\bar{t}$-induced background to the W^+W^- channel the l^+ and l^- both derive from real W decays and will generally be

the above, will eliminate both the $t\bar{t}$ *and* $q\bar{q}$ annihilation backgrounds, and achieve a very observable S/B ratio. Third, we note that this type of study of VV production at large m_{ϕ^0}, using the purely leptonic final states, is entirely the province of the SSC. Even at $L = 100$ fb^{-1}, only a few signal events are expected after the required cuts at the LHC and a clear signal would not emerge.

1.3. Overall Conclusions

The conclusion from these recent studies of the low intermediate mass region and the high mass region, is that we can now say with confidence that the full range of m_{ϕ^0} can be explored at the SSC. This important benchmark statement was not possible previously. However, there is no guarantee that nature has chosen the minimal SM. Indeed, as is well known (see Ref. [1] for a review) the SM suffers from naturalness and hierarchy problems that suggest that some type of non-minimal extension is required. Clearly, it is important to assess the degree to which one can explore the Higgs sectors of the most attractive non-minimal models.

3. The Minimal Supersymmetric Model

Among the theoretical approaches which go beyond the Standard Model, the supersymmetric extensions are particularly attractive in that they preserve the elementary nature of the Higgs bosons, while at the same time solving the naturalness and hierarchy problems. Further, supersymmetric GUT's are among those that yield a reasonable value for $\sin^2\theta_W$ at low energy and sufficiently small proton decay rates.[23] The simplest supersymmetric extension is the minimal supersymmetric model, in which the Higgs sector contains two doublet Higgs fields and is highly constrained. The physical Higgs bosons of the model are: two CP-even scalars, h^0 and H^0, with $m_{h^0} \leq m_{H^0}$; one CP-odd scalar, A^0; and a charged Higgs pair, $H^{\pm}$.† In the context of the MSSM, current experimental data from LEP indicates that $m_{h^0} \gtrsim 40$ GeV, $m_{A^0} \gtrsim 30$ GeV, $m_{H^\pm} \gtrsim 40$ GeV. As we shall see below, these lower bounds will be pushed to near m_Z after LEP-II completes its experimental search for $e^+e^- \to Z^* \to h^0A^0$ or Zh^0. At tree level, all the masses and couplings of the Higgs bosons are determined by just two parameters, conventionally chosen to be m_{A^0} and $\tan\beta = v_2/v_1$ (the ratio of vacuum expectation values of the neutral components of the Higgs fields which couple to up and down quarks, respectively). All other Higgs boson masses as well as the neutral sector mixing angle, α, and all couplings to quarks and vector bosons can be expressed in terms of these parameters. In particular, one finds $m_{h^0} < |\cos 2\beta| \min\{m_Z, m_{A^0}\}$, $m_{H^0} \geq m_Z$, and $m_{H^\pm} \geq m_W$. Further, for large m_{A^0}, $m_{H^0} \simeq m_{A^0} \simeq m_{H^\pm}$. The first relation above would imply

isolated.

† Classification of the neutral Higgs bosons by CP properties is possible in the MSSM because the Higgs sector is automatically CP conserving.

that the h^0 can be detected at LEP-II (assumed to have $\sqrt{s} = 200$ GeV), provided efficient b-tagging is possible and $L \sim 500$ pb^{-1} is achieved.[24,25]

However, at one loop,[26-31] additional parameters are required to fully determine the masses and couplings of all the Higgs bosons. Aside from m_{A^0} and $\tan\beta$, values for m_t and a number of supersymmetric model parameters (squark masses, μ and the $A_{b,t}$) must be specified. The most crucial result is that the one-loop corrections can boost m_{h^0} above m_Z, *i.e.*, beyond the reach of LEP-II, if $m_t \gtrsim 120$ GeV and $\tan\beta$ is not too small. If this occurs, then the h^0 must be searched for either at the LHC and SSC or at a higher energy e^+e^- collider. At the LHC/SSC, the search for the h^0 will use the techniques developed for an Intermediate Mass SM Higgs boson. At a e^+e^- collider, detection of the h^0 will be possible so long as $\sqrt{s} \gtrsim 300$ GeV (assuming $m_t \lesssim 200$ GeV) and adequate luminosity is available. In the following we present a more detailed survey of the sensitivity of such new supercolliders to the h^0 and the other Higgs bosons of the MSSM.

3.1. The Impact of Radiative Corrections on Masses and Couplings

Before proceeding, it is useful to first outline the impact of radiative corrections upon the masses and couplings of the MSSM Higgs bosons. Clearly, the most important point is that as m_t increases so does the upper bound on m_{h^0}; and, at the same time, the lower bound on m_{H^0} gets larger. The largest m_{h^0} values are attained in the large $\tan\beta$, large m_{A^0} corner of parameter space. For $m_t = 150$ GeV the largest value is slightly in excess of 108 GeV, while for $m_t = 200$ GeV the upper limit on m_{h^0} is about 138 GeV. Meanwhile, in the large $\tan\beta$, small m_{A^0} corner of parameter space are found the minimum m_{H^0} values, ~ 110 GeV (~ 141 GeV) for $m_t = 150$ GeV ($m_t = 200$ GeV). For $m_t = 100$ GeV the upper bound on m_{h^0} and lower bound on m_{H^0} are both near m_Z, as predicted at tree level. Next, let us recall that some of the most crucial couplings of the MSSM Higgs bosons are directly determined by $\cos^2(\beta - \alpha)$. A remarkable feature of the MSSM is that $\cos^2(\beta - \alpha)$ decreases very rapidly with increasing m_{A^0}, and in fact is highly suppressed over all of parameter space, except in the large $\tan\beta$, small m_{A^0} corner. These features were first observed at tree-level,[1] and continue to pertain after radiative corrections, although radiative corrections do decrease the suppression somewhat at every $\tan\beta$, m_{A^0} parameter choice. (More details can be found in, for instance, Refs. [32,33].) Regarding quark couplings, we note only that $t\bar{t}$ ($b\bar{b}$) couplings of the H^0 and A^0 tend to be suppressed (enhanced) at large $\tan\beta$, while those of the h^0 become SM-like at large m_{A^0}.

The importance of $\cos^2(\beta - \alpha)$ becomes apparent by recalling the pattern of the couplings of the h^0 and H^0 to VV ($V = Z$ or W) and ZA^0. Relative to the SM, the h^0VV and H^0VV couplings are proportional to $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$, respectively. In complementary fashion, the Zh^0A^0 and ZH^0A^0 couplings are proportional to $\cos^2(\beta - \alpha)$ and $\sin^2(\beta - \alpha)$, respectively. Thus, for instance, if the h^0 can be seen at an e^+e^- collider via $Z^* \to Zh^0$ (corresponding to the large

portion of parameter space where $\sin^2(\beta-\alpha)$ is large) then the $Z^* \to H^0A^0$ process will simultaneously be maximal if kinematically allowed. More generally, as we outline below, this complementary coupling pattern implies a no-lose theorem for MSSM Higgs detection at e^+e^- colliders. At the LHC and SSC, the most important consequences of these couplings and the behavior of $\cos^2(\beta-\alpha)$ are two: the WW fusion mechanism is never important for H^0 production when m_{H^0} is large,[‡] and WW and ZZ decay widths of the H^0 are always very much smaller than in the case of the SM ϕ^0. We also recall, at this time, that the CP-odd A^0 can have no tree-level WW, ZZ coupling,[§] implying that the same remarks apply to the A^0. Note, that the suppression of the WW, ZZ decays of the H^0 and A^0 implies that these Higgs remain quite narrow ($\Gamma < 2-3$ GeV) until the $t\bar{t}$ decay threshold is passed, unless the $b\bar{b}$ decays are greatly enhanced due to the value of $\tan\beta$ being very large.

With this brief outline of the basic features of the MSSM Higgs boson masses and couplings, we are now in a position to return to their phenomenology at the LHC, SSC and NLC (next linear e^+e^- collider).

3.2. NLC Phenomenology

The phenomenology of the next e^+e^- collider is best discussed by considering the exceptional corner of parameter space (small m_{A^0} and large $\tan\beta$), where $\cos^2(\beta-\alpha)$ is not suppressed, separately from the rest of parameter space, where it is suppressed. Our results are based on the study of Ref. [34]. Outside of the exceptional corner, once $\sqrt{s} \gtrsim 300$ GeV, the h^0 can always be seen (for any $m_t \lesssim 200$ GeV) via the $Z^* \to Zh^0$ and $e^+e^- \to \bar{\nu}\nu W^+W^- \to \bar{\nu}\nu h^0$ processes (to name the most important ones). Meanwhile,, the H^0 and A^0 will be detected in $Z^* \to H^0A^0$ and the $H^\pm$ will be found via $Z^* \to H^+H^-$ if $m_{A^0} \lesssim \sqrt{s}/2$ (recall that $m_{A^0} \sim m_{H^0} \sim m_{H^\pm}$ when m_{A^0} is large, independent of $\tan\beta$). In the exceptional corner of large $\tan\beta$ and small m_{A^0}, $\cos^2(\beta-\alpha)$ is near 1, m_{H^0} and $m_{H^\pm}$ are near their lower limits and m_{h^0} is substantially below its upper bound. Thus, if $\sqrt{s} \gtrsim 300$ GeV the h^0 will be found in $Z^* \to h^0A^0$, the $H^\pm$ will be found in $Z^* \to H^+H^-$, and the H^0 can be detected via either $Z^* \to ZH^0$ or $e^+e^- \to \bar{\nu}\nu H^0$. At $\sqrt{s} \sim 300-500$ GeV, an integrated luminosity of order 500 pb^{-1} is more than adequate for the above statements to apply, while for $\sqrt{s} \gtrsim 1$ TeV, $L \gtrsim 10$ fb^{-1} would be required. Thus, we see in brief why it is that a sufficiently energetic NLC with sufficient luminosity can see all the Higgs bosons of the MSSM.

3.3. SSC/LHC Phenomenology

Some examination of the relevant issues at tree level appeared early on in Refs. [1-3] (see also references therein) and related experimental studies for the

‡ For small m_{H^0} and any m_{h^0}, gg fusion dominates WW fusion.

§ However, there is a one-loop induced A^0 coupling to WW, ZZ; see Ref. [33].

SSC, and in Ref. [35] and related experimental studies for the LHC. Recently, the phenomenology of the MSSM Higgs bosons at the LHC and SSC has been re-examined after including radiative corrections in Refs. [13,32,33,36-38]. Here, I will summarize the results obtained in Refs. [13,32,33]. We shall consider m_{A^0} and $\tan\beta$ as our fundamental Higgs sector parameters, but, as noted above, to determine one-loop leading log radiative corrections we must also specify m_t, the (universal) squark mass, and other parameters that determine the amount of squark mixing. In all that follows we shall take $m_{\tilde{q}} = 1$ TeV and neglect squark mixing.[¶] Although LEP provides the lower bound for m_{A^0} noted earlier, there are currently no experimental constraints on $\tan\beta$. On the basis of renormalization group arguments it is generally expected that $1 \lesssim \tan\beta \lesssim m_t/m_b$.[1] Thus, we have considered the range $0.5 \leq \tan\beta \leq 20$. In addition, we must specify the chargino and neutralinos masses. These particles would dominate Higgs decays and strongly affect one-loop induced processes (such as $\gamma\gamma$ decays of neutral Higgs) if sufficiently light. The results which follow assume that the ino masses are all greater than 200 GeV (implying, in the minimal no-intermediate-scale GUT unification scheme, a gluino mass somewhat in excess of 1 TeV). In this case, we can explore $m_{A^0} \lesssim 400$ GeV without including the ino's in the Higgs decays, and, in addition, for such chargino masses they have pretty much decoupled from one-loop contributions to the $\gamma\gamma$ couplings of the neutral Higgs bosons. We also note that, for the squark mass assumed, squark loop contributions to the gg coupling of the neutral Higgs bosons are small.

In the following we wish to determine the extent to which one or more of the Higgs bosons of the MSSM can be detected throughout all of $m_{A^0} - \tan\beta$ parameter space at either LEP-II or the SSC/LHC hadron colliders. For LEP-II we determine the parameter regions over which the a) $Z^* \to Zh^0$ and b) $Z^* \to h^0A^0$ processes should provide a viable signal, by requiring 25 events, assuming $\sqrt{s} = 200$ GeV, $L = 500$ pb^{-1} and an overall detection efficiency of 25% (*i.e.* 0.2 *pb* of cross section is demanded). For the SSC and LHC, we considered, in Refs. [13,32,33], only the cleanest and least controversial detection modes for the MSSM Higgs. We adopted an integrated luminosity of $L = 30$ fb^{-1} — a reasonably achievable goal for both colliders. In the case of the neutral Higgs bosons the clean modes are the same as employed for the SM ϕ^0: c),d) detection of the $h^0, H^0 \to ZZ, ZZ^* \to 4l$ decay modes; and e),f) detection in the $t\bar{t}h^0, t\bar{t}H^0 \to l\gamma\gamma X$ final state. In the case of the $ZZ^* \to 4l$ mode, where backgrounds are negligible, we required 15 events after cuts. For the $ZZ \to 4l$ and the $l\gamma\gamma$ cases, we required $S/\sqrt{B} \geq 4$ after cuts. In the case of the charged Higgs boson, the only detection mode considered is g) $t \to H^+b$ where the $H^\pm$ is detected either directly via its decays to jets (as appropriate when $BR(H^+ \to c\bar{s})$ is big — true at small $\tan\beta$) or via an excess of $\tau\nu$ events over universality expectations (as appropriate when the $H^+ \to \tau^+\nu$ decay mode is large

¶ As $m_{\tilde{q}} \to m_t$, the radiative corrections vanish and one approaches tree level results, which are very close to those obtained for $m_t = 100$ GeV in the following analysis.

— $\tan\beta \geq 1$). Our specific criterion is derived from the detailed studies[39] that have shown that the high rate of $t\bar{t}$ production at the SSC allows detection of $t \to H^+b$ decays unless $BR(t \to H^+b)$ is quite small. Typically, a very significant effect in either the $H^+ \to jj$ or the $H^+ \to \tau^+\nu$ decay mode can be observed at the SSC for $L = 30$ fb^{-1} so long as $BR(t \to H^+b) \gtrsim 0.01$, even if double b-tagging is required to isolate the $t\bar{t}$ events of interest from background. We employ this BR lower bound as our discovery criterion. It is probably too conservative, as recent work[40] shows that single b-tagging (which is probably sufficient to eliminate backgrounds) gives adequate signal whenever $BR(t \to H^+b) \gtrsim 0.003$. However, the extra region of parameter space that would be covered by this relaxation of the discovery criterion is not very large.

Before presenting a representative summary graph, a few additional intuitive words are probably useful. Consider first the LEP-II modes. Our earlier discussion indicates that $Z^* \to Zh^0$ will be viable so long as it is kinematically allowed and one is not in the small m_{A^0}, large $\tan\beta$ parameter space corner, where the h^0ZZ coupling is suppressed. For $m_t = 100$ GeV the h^0 never gets so heavy that Zh^0 production is forbidden, and, therefore, this mode is visible everywhere except in the above-noted parameter space corner. For $m_t = 150$ GeV, the h^0 becomes too heavy when $m_{A^0} \gtrsim 100$ GeV and $\tan\beta \gtrsim 7 - 10$ (depending on m_{A^0}). For $m_t = 200$ GeV, the h^0 becomes too heavy over most of parameter space except for moderate m_{A^0} and $\tan\beta \lesssim 3$. Consider next the $Z^* \to h^0A^0$ detection mode. It is essentially always viable for parameter choices in the small m_{A^0}, large $\tan\beta$ corner, whatever the value of m_t (≤ 200 GeV). This is simply because not only is the required coupling substantial, but also the h^0 and A^0 both have small enough masses that the process is well below kinematic threshold.

Consider next the $4l$ mode. For $m_t \leq 150$ GeV, the h^0 is never sufficiently heavy ($m_{h^0} \gtrsim 130$ GeV is required) that it could (even with full strength coupling) have an observable $4l$ decay rate. By $m_t = 200$, if m_{A^0} is large enough (roughly $m_{A^0} \gtrsim m_Z$) the h^0 becomes heavy enough and has a sufficient fraction of the full SM-like ZZ coupling that its $ZZ^* \to 4l$ event rate exceeds the 15 event requirement. The detectability of the $H^0 \to 4l$ decays is equally sensitive to m_t. For $m_t = 100$ GeV, there is essentially no mass range for which the suppressed $H^0 \to ZZ \to 4l$ decays are not swamped by $H^0 \to t\bar{t}$. By $m_t = 150$ GeV, $H^0 \to 4l$ can be detected for $m_Z \lesssim m_{A^0} \lesssim 2m_t$ so long as $\tan\beta$ is not so big that the $4l$ mode is overwhelmed by $H^0 \to b\bar{b}$ decays. The upper limit above is, of course, fixed by the $t\bar{t}$ threshold, while the lower limit is determined by when m_{H^0} falls too far below the ZZ threshold (roughly $m_{H^0} \lesssim 130$ GeV). By $m_t = 200$ GeV, for small m_{A^0} the H^0 is heavier than the critical 130 GeV, and, in addition, has sufficiently substantial ZZ coupling that the $4l$ mode is visible. At larger m_{A^0} (but $m_{H^0} \leq 2m_t$ still), this coupling becomes progressively more suppressed, and at higher values of $\tan\beta$ the $4l$ decay is swamped by the $H^0 \to b\bar{b}$ decays. Once $m_{H^0} \geq 2m_t$, $t\bar{t}$ decays are dominant and the $H^0 \to 4l$ decays cannot be seen for any $\tan\beta$.

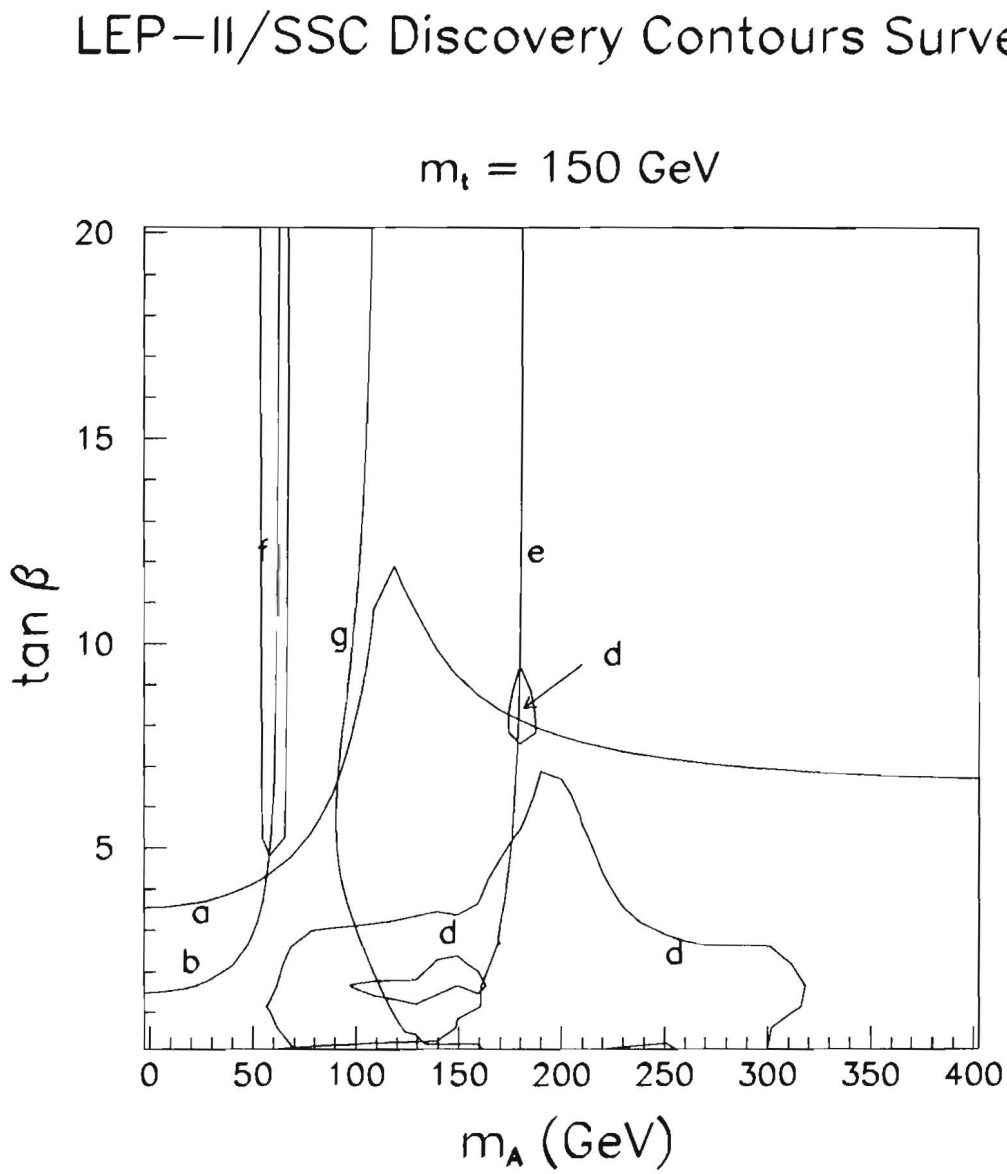

Figure 1: Discovery contours in $m_{A^0} - \tan\beta$ parameter space for the SSC with $L = 30$ fb^{-1} and LEP-II with $L = 500$ pb^{-1} for the reactions: a) $e^+e^- \to h^0 Z$ at LEP-II; b) $e^+e^- \to h^0 A^0$ at LEP-II; c) $h^0 \to 4l$; d) $H^0 \to 4l$; e) $Wh^0X \to l\gamma\gamma X$; f) $WH^0X \to l\gamma\gamma X$; g) $t \to H^+b$. We take $m_t = 150$ GeV. Discovery criteria are as stated in the text: ≥ 25 events for reactions a) or b) at LEP-II; $S/\sqrt{B} \geq 4$ for reactions c)-f); and $BR(t \to H^+b) \geq 0.01$ for g). The contour corresponding to a given reaction is labelled by the letter assigned to the reaction above. In each case, the letter appears on the side of the contour for which detection of the particular reaction *is* possible.

With regard to the $l\gamma\gamma$ mode, there is only the tiniest region of parameter space for which the W (generally suppressed) and quark loops combine to yield a $BR(H^0 \to \gamma\gamma)$ that is large enough for the H^0 to be visible in this channel. In the case of the h^0, the $l\gamma\gamma$ mode is always visible if it has sufficiently SM-like couplings that its $\gamma\gamma$ branching ratio is similar to that of the ϕ^0 of the same mass, and if it is sufficiently heavy ($m_{h^0} \gtrsim 80$ GeV) that $\gamma\gamma$ decays are not suppressed. Both criteria are satisfied, more or less independently of $\tan\beta$, so long as m_{A^0} is large enough. For $m_t = 200$ GeV, the radiative corrections cause m_{h^0} to reach the required mass region for smaller m_{A^0} than for $m_t = 150$ GeV, while at $m_t = 100$ GeV, m_{h^0} is large enough only at quite large m_{A^0}.

We are now in a position to present a sample summary graph. We have chosen the case of $m_t = 150$ GeV at the SSC. The graph, Fig. 1, shows that detection of one or more of the MSSM Higgs bosons will be possible either at LEP-II, or at the SSC, except in a window with $m_{A^0} \sim 120 - 150$ GeV and $\tan\beta \gtrsim 8 - 10$. The equivalent graph for $m_t = 200$ GeV shows that there is only a small gap ($m_{A^0} \sim 160$, $\tan\beta \gtrsim 10 - 15$) where no MSSM Higgs boson can be found. Although the region of parameter space that is covered by LEP-II is relatively limited for such a large m_t, at the SSC the $H^0 \to 4l$ channel becomes viable in all but the large m_{A^0}, large $\tan\beta$ region of parameter space (where $b\bar{b}$ decays of the H^0 suppress the $4l$ decays of interest). At $m_t = 100$ GeV, detection of the MSSM Higgs bosons is possible only over a very limited portion of parameter space (high m_{A^0} via the $l\gamma\gamma$ mode for the h^0), but LEP-II provides almost complete coverage. A more complete discussion of these results and the corresponding results for the LHC can be found in Refs. [13,32,33].

3.4. Conclusions for the Minimal Supersymmetric Model

The above remarks can be summarized by saying that the combination of LEP-II (with $\sqrt{s} = 200$ GeV, $L = 500$ pb^{-1}) and the SSC (with $L = 30$ fb^{-1}) comes close to providing a no-lose theorem: at least one of the MSSM Higgs bosons will be discovered at one or the other machine for any choice of the basic parameters m_t, m_{A^0}, and $\tan\beta$. In order for the coverage of the various detection channels to be sufficiently complete that one is equally close to a no-lose theorem at the LHC, the full enhanced luminosity of $L = 100$ fb^{-1} will be required.

4. Final Remarks

It is now clear that the design parameters if LEP-II and of the SSC will allow discovery of the Standard Model Higgs boson over the entire range of theoretically reasonable masses. The SSC will also be able to detect strong interactions between longitudinally polarized gauge bosons, if present. In the case of a light Higgs boson, the SSC will be able to check that such strong interactions are not present, and that VV scattering follows the perturbative prediction of the Standard Model.

In the case of the Minimal Supersymmetric Model, it is clear that LEP-II and the SSC combine to nearly guarantee that at least one of the Higgs bosons of the MSSM will be discovered at one or the other machine. For a light top quark, LEP-II will play the most important role, and sensitivity of the SSC to the MSSM Higgs bosons is likely to be small. However, if $m_t \gtrsim 140$ GeV, as preferred in current electroweak analysis at LEP, the SSC will allow discovery of one or more of the MSSM Higgs over a substantial segment of the basic $m_{A^0} - \tan\beta$ parameter space. Perhaps most importantly, if LEP-II discovers the light scalar Higgs, the SSC will have a substantial chance of finding the heavy scalar, the pseudoscalar, and/or the charged Higgs boson.

Of course, a sufficiently energetic e^+e^- collider with adequate luminosity would provide an even more ideal machine for the detection of either the SM Higgs boson or the MSSM Higgs bosons, provided they are not too heavy. However, to study strong $V_L V_L$ interactions at an e^+e^- collider will probably require $\sqrt{s} \gtrsim$ 2 TeV.[41]

Overall, it is clear that the accelerators of the next decade will almost certainly unlock the secrets of electroweak symmetry breaking, and provide many exciting discoveries that will point the way to the correct extension of the Standard Model.

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